

Flood frequency hydrology: 2. Combining data evidence

Ralf Merz¹ and Günter Blöschl¹

Received 7 December 2007; revised 30 April 2008; accepted 2 June 2008; published 23 August 2008.

[1] In a companion paper (Merz and Blöschl, 2008) we argue that it is very useful to expand the information beyond the flood sample at a site of interest to better represent the diversity of flood processes in estimating flood frequencies. In this paper we present a framework of how to combine different sources of information by hydrological reasoning to obtain more informed estimates of flood frequencies. These sources of information include the local flood peak sample and temporal, spatial, and causal expansion of information. As most of this information is independent, one would expect that the final estimate is more reliable than each of the individual sources, including the flood peak sample alone. To illustrate the proposed framework, four examples from Austria are given. In all four examples the statistical analyses of the flood records do not fully represent the site-specific flood behavior in the light of the more complete information. The strengths of the proposed framework are its flexibility, in that more weight can be given to sources that are known with better confidence than others, and the ability to account for local particularities of catchments in terms of hydrological processes and data availability.

Citation: Merz, R., and G. Blöschl (2008), Flood frequency hydrology: 2. Combining data evidence, *Water Resour. Res.*, 44, W08433, doi:10.1029/2007WR006745.

1. Introduction

[2] In a companion paper [Merz and Blöschl, 2008], we argue that expanding information beyond the flood sample is very useful for accurately estimating flood frequencies. The expansion of information can be grouped into three types: Temporal, spatial and causal expansion. Temporal information expansion consists of collecting information on the flood behavior before or after the period of discharge observations. Spatial information expansion uses flood information from neighboring catchments to improve the flood frequency estimates at the site of interest. Causal information expansion analyses flood generation processes. Some pieces of information used in this process will be quantitative and a range of formal methods exists for combining the expanded information with the flood peak samples. Such methods relate to historical flood data or palaeofloods [e.g., Benito and Thordycraft, 2005], regional flood data [e.g., Dalrymple, 1960; Bobée and Rasmussen, 1995; Merz and Blöschl, 2005] and flood processes based on the derived flood frequency approach [e.g., Eagleson, 1972; Sivapalan et al., 2005]. Other pieces of information will be proxy data or indicators, on changing flood processes with increasing flood magnitude or landscape characteristics for example. Proxy data can be combined with quantitative estimates by Bayes's statistics [Wood and Rodriguez-Iturbe, 1975; Kirnbauer, 1981], for example, although the formulation of suitable indices is usually not straightforward.

[3] In the literature, usually, one piece of information is used individually and different flood estimation methods are often used as alternatives. In the *UK Flood Estimation Handbook* [*Institute of Hydrology*, 1999, Book 1, Table 5.1– 5.4], for example, guidelines are given on the choice of method for UK conditions. The alternatives to be selected from are local flood statistics, regional flood statistics and rainfall-runoff modeling, and the recommended choice depends on the available data. *Pilgrim and Doran* [1993] present quantitative criteria for choosing between either design-rainfall based methods or flood frequency analysis. They note that the choice of method is possibly the most important decision in flood estimation.

[4] In a practical case study, a range of different types of information may be available, so different estimation methods can be applied. One would expect that flood estimates may benefit from a synthesis of these methods, as they are usually based on different assumptions and different data. Only a few studies in the literature attempt this type of synthesis. One notable example is the study by *Gutknecht et* al. [2006] who propose a multipillar approach for estimating design floods of dams. In their research, local flood statistics, regional flood statistics, rainfall-runoff modeling and envelope curve analysis are combined on the basis of their respective uncertainty ranges and expert judgment. The combination may indeed be difficult as each of the methods involved is based on different information, and so different importance needs to be attached to each source in the final assessment of the flood estimate. Also, the nature of proxy information may very much depend on the local situation. Formalizing the combination may hence be difficult.

[5] The aim of this paper is to propose a framework of how to combine different pieces of information in flood frequency hydrology. The framework is illustrated by four

¹Institute for Hydraulic and Water Resources Engineering, Vienna University of Technology, Vienna, Austria.

Copyright 2008 by the American Geophysical Union. 0043-1397/08/2007WR006745\$09.00



Figure 1. Schematic of the proposed estimation procedure in flood frequency hydrology.

examples from Austria to address a range of hydrological conditions and data availabilities.

2. Combination of Information

[6] The concept of "flood frequency hydrology" put forward in the companion paper highlights the importance of using a maximum of hydrologic information from different sources and a combination based on hydrological reasoning. The first step in the proposed framework (Figure 1) is to compile flood peaks at the site of interest plus three additional types of information: temporal, spatial and causal information. From some sources of information quantitative estimates of flood frequencies can be obtained by formal methods, including confidence intervals or uncertainty bounds. One example are the local flood peak samples themselves. From other sources, quantitative estimates can be obtained, but the uncertainty bounds are not well defined. An example is flood estimates in hydrologically similar catchments. However, some understanding of the magnitude of this uncertainty may exist by the analyst. Still other sources of information may not allow to make quantitative estimates but can be represented by indicators or proxies of what flood magnitudes are likely, guided by hydrological reasoning. An example is geomorphologic landscape characteristics. Conversely, for many pieces of information it may be prudent to focus on the ranges of possible estimates rather than on the estimates themselves. In local flood statistics, a range of estimates may result from a reasonable fit of several distributions to the observed data. Historical flood data may only allow us to give a range of estimates owing to large uncertainties. Spatial information may lead to a range of estimates when using several regionalization schemes or parameters of the regionalization

schemes all of which may be consistent with the regional information. Causal information may result in a range of estimates due to using different methods, different data, and uncertainty in the expert judgment.

[7] When comparing these pieces of information two possible cases exist (Figure 1). In the first case, the different pieces of information are consistent within their uncertainty ranges. This means that the uncertainty ranges of the four types of sources overlap and/or the flood estimates cluster. In such a case, the combined estimate of the flood frequency curve will lie in or near the overlapping range. One may use Bayesian statistics or fuzzy methods to take the relative uncertainties of the individual estimates into account in obtaining the final estimate. In the present paper, the final estimate was simply obtained by expert judgment, considering the relative uncertainties of the component sources of information. In the second case, the different pieces of data evidence are inconsistent. This may be because quantitative estimates of the individual methods differ beyond their uncertainty bounds or proxy data shed doubt on the magnitudes of quantitative estimates. There are of course many potential sources of inconsistencies including data errors, biases in the estimation methods, and local effects that are not apparent in the regional data. In such a case the proposed framework suggests to go back to the data and methods used and attempt to understand the inconsistencies. In the light of more than one estimate, data interpretations may change. If inconsistencies cannot be explained on the basis of the available hydrological information, other sources of information may be sought that, preferably, represent different aspects of the flood processes in the catchment and/or along the reach of interest. Understanding the inconsistencies is indeed considered an important step in the

procedure as it will enhance the reliability of the final flood frequency estimates. If the inconsistencies cannot be removed one would have to contemplate very large uncertainties in the estimates which would have to be taken into account in the application of the estimates in, say, hydraulic design. When comparing the first case of consistent data sources with the second case of inconsistent data sources one would expect that the former will be associated with less overall uncertainty. Understanding the inconsistencies will help reduce the uncertainties of the latter case.

[8] It is unlikely that the various sources of information are fully dependent because of the different data, concepts and methods used. It is hence clear that the synthesis will reduce the uncertainty of the estimates beyond that of a single method alone. One may argue that there is a degree of subjectiveness involved in combining the individual estimates. For simplicity we are adopting here a combination by expert judgment while more formal methods exist. While this combination does involve an element of subjectivity it allows one to capture subtleties of processes that cannot be easily incorporated into a quantitative scheme. This will be illustrated later in this paper. Particularly, if the quantitative data are sparse and/or inaccurate, proxy data and hydrological reasoning will become more important. However, formal methods may be no less subjective. As Stedinger et al. [1993] noted, the basic problem of frequency analysis is an information problem and there is never sufficient information available to exhaustively describe the flood frequency behavior of a catchment. Each method involves assumptions, for example, choice of distribution function, choice of regionalization method, and choice of method for accounting for climate fluctuations with respect to the observational window [Moran, 1957]. This choice will introduce some subjectiveness into the process which is unavoidable. We argue that, with an increasing amount of information on different aspects of flood processes, the choice will be more informative even if some of the methods used are less formal than in the traditional procedure. Given that the process understanding of hydrologists provides a unifying principle, the proposed procedure may in fact be less subjective than the traditional one. In a similar fashion, a medical doctor will base his/her decision on various sources of information. Rather than running regressions on the data, he/she will typically combine the diagnostic findings by expert judgment. While two doctors will not necessarily prescribe exactly the same treatment in any one case, the decisions are based on a similar medical background education, so there is some coherence. Also, the judgment process allows to account for the uniqueness of individual patients. In a similar way, judging flood estimates based on various sources of information assists in accounting for the local particularities of a catchment and/or reach.

[9] The proposed framework can be used with any method of the component processes, including formal and non formal methods. Choice of method may depend on data availability, personal preferences and national traditions. For example, methods of spatial information expansion may range from a simple comparison of neighboring catchments to formal regionalization schemes such as the index flood approach [*Dalrymple*, 1960], multiple regressions

[*Tasker*, 1987] and the Region of Influence approach [*Burn*, 1990].

3. Examples

[10] Four examples from Austria are presented in this paper to illustrate different aspects of the flood frequency hydrology framework. In the first example, the Kamp river at Zwettl, a large amount of information on flood behavior is available and the different methods of temporal, spatial and causal information expansion give consistent results. In the second example, Pulkau at Zwingendorf, which is located just northeast of the Kamp, less information is available and proxy data are used to give confidence in the individual quantitative methods. The third example, Drau at Drauhofen, is a much larger catchment, so more emphasis is on the flood routing processes than in the first two examples. The last example, Zöbernbach at Kirchschlag, represents a case where quantitative methods of temporal and spatial information expansion give inconsistent results, but soft data provide diagnostic findings on the magnitude of the flood frequency estimates. The examples are taken from a case study in which 30-, 100- and 200-year return period flood discharges were estimated for 26,000 km of Austrian streams [Merz et al., 2008]. We have hence chosen to use the same flood estimation methods as in that case study. Specifically, the first three moments of the annual flood peak distribution, mean annual flood (MAF), coefficient of variation (CV) and skewness (CS) were first estimated directly from the flood data and then for each of the expanded methods (temporal, local and causal expansion of information). T-year floods were estimated from the moments using the Generalized Extreme Value (GEV) distribution. Previous analyses [Merz and Blöschl, 2005] indicated that the GEV distribution is flexible enough to accommodate the flood frequency situations encountered in Austria. However, it should be stressed that the moments are used here only for illustration purposes and alternative methods (such as flood quantiles and probability weighted moments) could be used very much a similar way as could be other distribution functions.

3.1. Example 1: Kamp at Zwettl

[11] The first example is the Kamp river at Zwettl which is located in northern Austria and has a catchment area of 622 km². For the Kamp at Zwettl, annual flood peak data from 1951 to 2004 are available (Figure 2). The statistical analyses of the flood peaks are dominated by the extreme flood event in August 2002. In August 2002 a Vb-cyclone [Mudelsee et al., 2004] carried warm moist air from the Adriatic region and caused persistent rainfall over the Kamp region. This resulted in a peak flow of 460 m³/s which is three times the second largest flood on record. Weibull plotting positions would assign a return period of 55 years to this flood. Owing to the extreme event in 2002 a fitted flood frequency curve is rather steep with MAF, CV and CS of 63 m^3/s , 0.98 and 5.21, respectively. With these moments, a GEV distribution gives a 100-year flood runoff (HQ₁₀₀) of 293 m³/s. Bulletin 17B [U.S. Geological Survey, 1982] defines outliers as "Data points which depart significantly from the trend of the remaining data." Obviously this is the case for the 2002 flood and indeed statistical tests, such as threshold analyses [e.g., Stedinger et al., 1993]



Figure 2. (a) Time series of maximum annual peak discharges of the Kamp at Zwettl (622 km^2). Peak discharges reconstructed from water table data and historical flood discharges are shown in gray. (b) Plotting positions based on observed flood data (black circles) alone, based on extended data (observations and reconstructed discharges) (plusses) and extended and historical flood data (open circles) of the Kamp at Zwettl. The range of the statistical estimates and the estimates from the temporal information expansion are in shown in dark and light gray, respectively.

identify the 2002 flood event as an outlier. From a statistical point of view one could argue that the 2002 flood should be excluded in order not to distort the statistical properties of the remaining data. Without the extreme event in 2002 the local flood moments MAF, CV and CS are 57 m^3/s , 0.51 and 1.14, respectively. In particular, the skewness is much

smaller than that from the sample including the 2002 flood. The HQ_{100} from the sample without the 2002 flood is 148 m³/s. When extrapolating this flood frequency curve to large return periods one would assign a return period of 2000 to 10,000 years to the 2002 event. If one takes the samples (either with or without the 2002 flood) at face value one assumes ergodicity. When including the 2002 flood, the statistically estimated return period of such an extreme event decreases, which implies the assumption that such extreme events occur regularly, while when excluding the event, the statistically estimated return period of such an extreme event is very high, which implies the assumption that such events occur very rarely. The flood frequency curves of these two cases, i.e., fitting a GEV distribution to the observed flood sample including the event 2002 and not including the event 2002, span a range of statistical estimates which is shown in dark gray in Figure 2b. For other distributions there is a similar effect which is less dramatic for two parameter distributions such as Gumbel: HQ₁₀₀ (with $2002) = 279 \text{ m}^3/\text{s}$ and HQ₁₀₀ (without 2002) = 156 m³/s, but can be stronger for other distributions such as Pearson III: HQ_{100} (with 2002) = 336 m³/s and HQ_{100} (without 2002) = 146 m³/s. There is a similar sensitivity for other parameter estimation methods. For example, using GEV and L-Moments, HQ_{100} is 288 m³/s for the sample with 2002, and 160 m³/s, when 2002 is excluded from the sample. In the Kamp example formal uncertainty distributions that reflect the sample uncertainty are not particularly helpful as they assume ergodicity. The range of plausible flood estimates in Table 1 and Figure 2b is hence taken as the range of estimates with and without the 2002 flood.

[12] To expand information into the past, flood discharges were reconstructed from water stage data [Gutknecht et al., 2002] for the period 1896 to 1947 (Figure 2a). The reconstructed data indicate that a number of large floods occurred in the first half of the twentieth century, while floods tended to be lower in the second half. To further expand information into the past and to assess the probability of the 2002 event, historical flood information is used. A survey of the local archives [Wiesbauer, 2007] reports that the three largest historical floods in the past 500 years occurred in 1655, 1803 and 1829 (Figure 2a). The runoff discharge of these events is highly uncertain but, for a historic analysis, the relative magnitudes as compared to the 2002 flood suffice. Information on inundation areas indicate that the water levels of the 1655 and 1829 events ranged around the 2002 event but these two events were caused by ice jams, so the discharges were likely smaller than those of the 2002 flood. The inundated area of the 1803 event was

Table 1. Combination of Data Evidence for the Zwettl Catchment (622 km²)

Type of Information	Data and Method	MAF (m ³ /s)	CV	CS	HQ100 (m ³ /s)
Statistics	methods of moments, GEV distribution, with or without outlier	57-63	0.51-0.98	1.14-5.21	148-293
Temporal	floods reconstructed from water stages; historical flood information	63	0.7 - 0.9	4	225-273
Spatial	top-kriging without local data	62	0.81	2.7	243
Causal Combination	Gradex; runoff coefficients	63 63	0.65 - 0.85 0.8	$4-6 \\ 3.5$	215-262 248



Figure 3. Map of mean annual flood discharges normalized to a standard catchment area of 100 km^2 (MAF100) (equation (1)) and long-term mean annual precipitation (MAP) for the Kamp and Pulkau regions. MAF100 includes the 2002 flood. Station 3 is Zwettl, and station 13 is Zwingendorf.

much larger than in August 2002 but there were apparently backwater effects from the Danube which were less pronounced in 2002, so the associated flood discharges can be assumed to be smaller than for the 2002 event. These analyses hence suggest that the 2002 event was probably the largest event since 1650. In Figure 2b the plotting positions of the flood data are shown. For the observed floods and the reconstructed floods Weibull's formula is used. For the flood sample including historical floods equations 18.6.11 and 18.6.12 from Stedinger et al. [1993] are used. The striking point is, of course, the empirical probability of the largest flood event which is more than 400 years if historic flood information is used. Also, the flood frequency curve is less curved and the 2002 flood is no apparent outlier. If one fits a GEV distribution manually to the extended data, MAF is 63 m^3/s , CV is between 0.7 and 0.9 and CS is about 4. The range of flood frequency estimates given by these moments is shown in light gray in Figure 2b and is smaller than the range one would assign to the statistical analysis of the observed flood peaks (dark gray).

[13] Spatial information expansion is based on using flood information from neighboring catchments. A map of mean annual flood discharges (MAF) estimated from local flood data in the Kamp region and the Pulkau region (example 2) is shown in Figure 3. To visualize MAF without the first-order effect of catchment area, MAF has been normalized to a nominal catchment area of $\alpha = 100 \text{ km}^2$, by

$$MAF_{\alpha} = MAF \cdot A^{\beta} \cdot \alpha^{-\beta}, \tag{1}$$

where A is catchment area, and $\beta = 0.33$ was obtained from an analysis of regional flood data. Figure 3 indicates that MAF_{α} has a tendency to decrease from west to east. One reason of this trend appears to be long-term mean annual precipitation (MAP) which is also shown in Figure 3. In the high-elevation catchments in the west MAP is larger than 700 mm/a. With decreasing catchment elevation toward the east, MAP decreases to less than 500 mm/a along the Pulkau river. This is consistent with the larger MAF_{α} in the west (e.g., Zwettl (3), Neustift (1)), and smaller MAF_{α} in the east (Pulkau (10 + 13), Schmida (11) and Göllersbach (12), numbers: see Figure 3).

[14] Quantitative estimates of flood frequencies based on neighboring catchments can be obtained by various formal regionalization schemes. In work by Merz and Blöschl [2005] the predictive performance of various types of automatic regionalization methods was examined on the basis of a jack-knifing comparison for 575 Austrian catchments indicating that a geostatistical method outperformed other methods such as regressions and the Region of Influence approach. A geostatistical regionalization method known as top-kriging was hence chosen in this paper to regionalize the flood moments. Top-kriging [Skøien et al., 2006] takes both catchment area and the river network structure into account. The plusses in Figure 4 represent the regional estimates of the specific 100-year flood Q_{100} at the gauging stations in the region obtained from neighboring catchments by top-kriging, without using local flood data. To combine the regional estimates with local statistics and temporal information expansion, the ranges of the statistical estimates, spanned by the statistics including the 2002 flood (open circles) and the statistics without the 2002 flood (diamonds) are shown in Figure 4 in dark gray for the Kamp region. For most of the gauging stations of the Kamp region, the local Q₁₀₀ discharges (including the 2002 flood) are higher than the regional estimates. This is because outside the Kamp region the 2002 flood was less extreme, and top-kriging uses information from both inside and outside the region. The regional estimates of the first three moments at Zwettl are MAF = $62 \text{ m}^3/\text{s}$, CV = 0.81



Figure 4. Discharge-area diagram of the Kamp and Pulkau regions. Specific 100-year flood discharges derived from locally observed data are shown as open circles. Statistical estimates from local flood samples where the 2002 flood peaks are excluded are shown as diamonds. Regional estimates using flood data from neighboring station are shown as plusses.

and CS = 2.7 (Table 1) which fit well with the flood frequency estimates from the temporal information expansion (also see light gray shading in Figure 4). The regionally

estimated CS is slightly smaller than CS from temporal information expansion which can be explained by the smaller number of outliers outside the Kamp region.

[15] The most natural way of causal information expansion is to derive flood frequencies from rainfall information. The main benefit of using rainfall information in Austria is that available rainfall records are usually much longer than the flood records. Rainfall records are typically available for 100 years or more, while flood records are typically available for the past 50 years. A simple derived flood frequency model is the Gradex method [Guillot, 1972; Naghettini et al., 1996] which is based on the assumption that, beyond a threshold return period, any additional rainfall produces a corresponding increase in runoff. While the assumption of a direct correlation of flood and rainfall frequencies is a subject of debate, the method did provide useful information of flood estimates at large return periods for Austrian catchments [Merz et al., 1999]. To apply the Gradex method to the Kamp river at Zwettl, 88 years of observed maximum annual daily rainfall of the nearby rainfall station Rapottenstein were combined with the local flood data (Figure 5a). Excluding the 2002 flood event from the local flood data resulted in $Q_{100} = 250 \text{ m}^3/\text{s}$ (dashed line in Figure 5a). Although the Gradex method in this example does not include the extreme 2002 event, the steepness of the flood frequency curve significantly increases beyond the threshold return period. This means that the longer rainfall information indicates that the flood runoff at large return



Figure 5. (top) Flood frequency plots and (bottom) runoff coefficients of the associated flood events plotted against the return periods of the flood peaks. (left) Kamp at Zwettl. (right) Pulkau at Zwingendorf.



Figure 6. Topographic map of representative landforms in the Zwingendorf catchment. Typical of the Pulkau region are large-scale artificial drainage systems and river regulations.

periods may be higher than suggested by locally observed flood data and hence the higher-order moments are likely larger.

[16] The change in the flood generating mechanisms with the magnitude of the event may also give guidance on how to extrapolate the flood frequency curve to large return periods [see Sivapalan et al., 1990]. To this end, event runoff coefficients calculated from runoff data by Merz et al. [2006] for the period 1980-2003 have been plotted against the Weibull plotting positions of the associated flood peaks in Figure 5b. For small events, the runoff coefficients range between 0.1 and 0.4 and increase moderately with increasing return period of the flood peaks. For the two largest flood events, the runoff coefficients are about 0.6. The second largest event is the May 1996 flood where prior snowmelt had significantly increased antecedent soil moisture [Komma et al., 2007]. The largest event is the August 2002 flood. The low runoff coefficients for smaller flood events are related to soils. The main geological units of the Kamp catchments are granite, gneiss and schist. Weathering has produced sandy soils of large storage capacities which may be up to 60 mm [Blöschl et al., 2008]. However, if rainfall is large, the storage capacities may be exceeded which increases the runoff coefficients. Clearly, large flood events at Zwettl differ from smaller events not only by the magnitude of the rainfall but also by higher runoff coefficients. This analysis suggests that the flood frequency curve is likely steeper than the local statistical estimates excluding the 2002 flood hence CS should be larger, perhaps on the order 4 or more (Table 1) which is consistent with the trend of the Gradex method.

[17] In the Kamp example the range of estimates based on the causal expansion of information is in agreement with the estimates based on temporal and spatial expansion of information. The three types of additional information all fall within a range that is narrower than that from flood frequency analysis. The most plausible moments, considering all sources of information (Table 1) is hence MAF = $63 \text{ m}^3/\text{s}$, CV = 0.8 and CS = 3.5 which translates into a 100-year flood of 248 m³/s.

3.2. Example 2: Pulkau at Zwingendorf

[18] The second example is the Pulkau river at Zwingendorf (372 km² catchment area) which is located in the flatlands of northern Austria, northeast of the Kamp (Figure 3, station 13). The geology consists of impervious layers of marl and clay [Wiesbauer, 2005] which have led to the development of large-scale wetlands along the Pulkau, Schmida and Göllersbach (Figure 3). The wet soils and high dynamics of meandering rivers due to flooding have limited the agricultural use of the region, so the wetlands were drained by a dense network of artificial channels in the middle of the 19th century. Today, the Pulkau river near Zwingendorf and the tributaries are regulated in straight channels (Figure 6). For the Pulkau at Zwingendorf stream gauge 38 years of flood data from 1967 to 2004 are available (Figure 5c). The mean annual flood discharge is about 8 m³/s. The observed flood frequency curve is rather flat with CV = 0.7 and CS = 0.96 which gives $HQ_{100} = 26 \text{ m}^3/\text{s}$. No extreme floods, such as the 2002 event in the nearby Kamp catchment, have been observed in the Pulkau. However, the cross sections of the Pulkau river, constructed during river regulation works in the first half of the twentieth century are large compared to the observed runoff since 1967. This indicates that, historically, large floods have occurred, and it is possible that the flood sample is not representative of the longer past because of clustering of wetter and drier decades with higher and lower floods. Historical flood data may shed light on this but are unavailable in the Pulkau.

[19] A regional comparison with neighboring catchments suggests that the specific flood discharges in the Pulkau are indeed very low (Figure 4). They are only about a fifth of those at Zwettl, for example. The low flood discharges are partly related to the lower rainfall in the Pulkau catchment. The Pulkau region is located at the western edge of the Pannonian climate domain, which has a continental climate with warm and dry summers, and cold winters without significant snowfall. Long-term mean annual precipitation in the Pulkau region is about 500 mm/year which makes the Pulkau one of the driest regions in Austria (Figure 3). However, the dense drainage system is perhaps more important for the low observed flood discharges as the soils tend to be dry and no wetlands exist any longer. In the Kamp region, where almost no artificial drainage systems exist, mean annual precipitation is only 30% higher but the specific flood discharges are three to almost 10 times higher (Figure 3). The regionalized flood moments at Zwingendorf based on top-kriging without using local flood data are MAF = 9.2, CV = 1.17 and CS = 4.2 indicating that, in particular, the skewness is much higher than that of the local estimate (Table 2). As an alternative, multiple regressions have been used with long-term mean annual precipitation, the 95% quantiles of hourly rainfall and mean runoff coefficients as explanatory variables which give MAF = 14.5 m^3 /s, CV = 0.55 and CS = 2.97 for Zwingendorf. The

Type of Information	Data and Method	$\frac{MAF}{(m^3/s)}$	CV	CS	HQ100 (m ³ /s)
Statistics	methods of moments, GEV distribution	8	0.7	0.96	26
Temporal					
Spatial	top-kriging without local data; multiple regression	9.2-14.5	0.55-1.17	2.97-4.2	43-49
Causal	Gradex:	8	+	+	51
	rainfall analysis; runoff coefficients	8-8.5	0.9-1.5	4-5	35-56
Combination		8.5	1.15	4.5	45

 Table 2. Combination of Data Evidence for the Zwingendorf Catchment^a

^aCatchment is 372 km². Plusses indicate that a piece of information suggests larger moments than the local flood data.

two types of regionalization approaches cover a range of possible regional estimates and are shown in Figure 5c as a light gray band. Some of the donor catchments that have been used for the regionalization are in the neighboring Kamp and Thaya regions where CV and CS are large owing to the 2002 flood. Using these regional flood properties for Zwingendorf is, of course, only meaningful if one finds indicators of the potential for similarly large floods to occur in Zwingendorf by analyzing causal factors. Zwingendorf was hardly affected by the 2002 flood, and it is now of interest to examine whether similarly large rainfalls can occur in the Pulkau region.

[20] In Figure 7a the rainfall depths of extreme rain storms in the Kamp and Pulkau region between 1947 to 1997 are plotted against the burst duration. The plotted events are part of a large regional data set, provided by the Austria Hydrographic Services which consists of storms that exceed a rainfall depth P (mm),

$$P = \gamma \cdot d^{\delta},\tag{2}$$

where d is event duration (min), γ is 2.24 and δ is 0.5. In Figure 7a, plusses represent events in the Kamp region,

open circles represent events in the Pulkau region before 1967, the beginning of flood observations at Zwingendorf, and solid circles represent events in Pulkau after 1967. Obviously, similar rainfall depths have been observed in the two regions. There is a tendency for higher long-duration events to occur in the Kamp, particularly in the highelevation western part, and these events are mostly synoptic or frontal type storms resulting from orographic enhancement of westerly airflows. There is a tendency for higher short-duration events to occur in the Pulkau region which are mainly convective storms. In the dry continental Pannonian climate more energy is available to trigger convective storms. The rainfall analysis suggests that, while there are differences in the rainfall regime, the overall magnitudes of extreme storms are similar, so the T-year floods may be larger than what is indicated by the local flood record at Zwingendorf. Moreover, rainfall events with a depth of more than 40 mm have not been observed in the Pulkau region since 1967, but did occur before then (Figure 7a). This indicates that the flood record of Zwingendorf includes decades without large rainfall events and hence may not be representative of the population of floods. A similar trend is indicated by the maximum annual daily precipitation data at



Figure 7. (a) Depth-duration diagram of rainfall events exceeding the threshold in equation (2) in the Kamp and Pulkau regions. Open circles represent events in the Pulkau region before 1967, the beginning of flood observations at Zwingendorf, while solid circles represent events in Pulkau after 1967. Plusses represent events in the Kamp region. (b) Maximum annual daily precipitation for the Mailberg rainfall station in the Zwingendorf catchment. Grey bars indicate the period before the beginning of flood observations at Zwingendorf.

Mailberg in the Zwingendorf catchment (Figure 7b). Large rainfall depths have been observed between 1910 and 1915, between 1935 and 1945, and in particular between 1951 and 1957, but no large rainfall depths have been observed since 1967. This supports the above finding that the flood record may underestimate flood frequency and suggests that, in particular, CV and CS should be larger than those estimated from the local flood record.

[21] Using the rainfall data from Mailberg in the Gradex method (Figure 5c) results in a rather steep flood frequency curve beyond the threshold return period with a 100-year flood of 51m³/s. This is about twice that estimated from local statistics (Table 2). An additional analysis of the causal factors at Zwingendorf examines event runoff coefficients (Figure 5d). For small flood events with return periods of less than 5 years, runoff coefficients are always less than 0.2 and, in fact, usually less than 0.1. They increase dramatically with increasing return period up to 0.4 for a 10-year flood. Unfortunately, all flood events with return periods higher than 10 years occurred before 1980 so no runoff coefficients were available in the database used. However, as rainfall becomes more extreme, one would expect that there is a continuing trend of increasing runoff coefficients. The runoff coefficients at Zwingendorf increase much more strongly with the return period than they do in the Kamp (Figure 5b). From a hydrological perspective this is hardly surprising as one would expect a more nonlinear response in the dryer Pulkau catchment. One would hence expect larger CV and CS than in the Zwettl (Table 1). In particular, the comparison of the analysis of runoff coefficients and the analysis of extreme rainfalls suggests that MAF should be slightly larger, and CV and CS should be significantly larger than those of the flood sample. MAF, as assessed from the causal analysis, is assumed to lie in the range between 8 m³/s and 8.5 m³/s, CV between 0.9 and 1.5, and CS between 4 and 5 (Table 2). The associated quantiles are shown as a dark gray band in Figure 5c. The range is relatively large because only qualitative information on the flood frequency behavior is extracted from the analysis of rainfall and runoff coefficients. However, the causal analysis does corroborate the regional analysis in that CV and CS should be larger than what the local flood record suggests. When combining all of the above information (Table 2), plausible moments are MAF = 8.5 m³/s, CV = 1.15 and CS = 4.5 which translate into a 100-year flood of 45 m^3/s .

3.3. Example 3: Drau at Drauhofen

[22] The third example is the Drau at Drauhofen catchment in southern Austria which is much bigger (3674 km²) than the catchments of the first two examples. For a statistical analysis, 29 annual maximum flood peaks from 1974 to 2002 are available (Figure 8a). The moments of the flood sample are MAF = 620 m³/s, CV = 0.21 and CS = 0.33 which give HQ₁₀₀ = 957 m³/s.

[23] To expand the flood information into the past, the flood record of Amlach (4790 km²) is analyzed which lies 15 km downstream of Drauhofen. At Amlach, 101 years of continuous discharge measurements, from 1901 to 2002, are available (Figure 8b). The striking point in the flood sample are the large floods in 1965 and 1966. The extreme flood runoff in these 2 years was caused by heavy and persistent rainfall covering all of southern Austria associated with

low-pressure areas over the Adriatic sea. The flood events in 1965 and 1966 are the two highest observed flood peaks at all gauging stations along the Drau river that were operational at that time. Obviously, similarly large flood peaks occurred at Drauhofen in 1965 and 1966, but they are not included in the flood sample. For the time period of available flood observations at Drauhofen (1974 to 2002), the flood moments at Amlach are MAF = 690 m³/s, CV =0.22 and CS = 0.21 but for the complete 101-year observation period from 1901 to 2002 the flood moments are MAF = 720 m³/s, CV = 0.32 and CS = 2.36 which is mainly due to the 1965 and 1966 floods. For the same period, the moments at Amlach and Drauhofen are similar, so one can assume that Drauhofen had a similar flood regime before 1974. From this analysis, plausible CV and CS at Drauhofen are hence 0.32 and CS = 2.36.

[24] In a similar vein, historical flood data point to an increase in the higher flood moments. Rohner et al. [2004] provide information on historical flood events at the Drau river. Although historical flood information is subject to high uncertainty, it is evident that major flood events occurred at Drauhofen in 1567, 1632, 1767, 1810, 1851, 1882 and 1889. In the historical archives, it is reported that particularly the floods in 1810, 1851 and 1882 caused significant damage on bridges and the Drauhofen castle which is near the gauging station. From the historical sources no flood discharges could be assigned to the Drau river at Drauhofen, but more detailed information on historical floods is available for Villach which is about 45 km downstream of Drauhofen [Merz and Blöschl, 2008]. An analysis of the observed floods at Drauhofen and Villach shows a high degree of similarity in the flood variability. One can hence assume that this also holds for the historical events which suggest CV and CS of 0.35 and 1.3, respectively. The two methods of expanding information into the past, the historical flood analysis and the comparison to longer time series of the neighboring Amlach catchment, result in a similar estimate of CV, but CS differs significantly (Table 3). Although 101 years of observation are available at Amlach, a CS of 2.36 results from the two extreme floods in 1965 and 1966. This indicates that not even the 101-year period may be fully representative of the population of flood events, so the smaller value of CS = 1.3from historical events may be more plausible. It is interesting that the ergodicity of such a long sample can be challenged.

[25] In large catchments, such as the Drauhofen catchment, routing effects can be very important. One tool to assist in the assessment of routing effects are longitudinal profiles, in which T-year flood runoff is plotted against stream length. In Figure 9, the 100-year floods of the Drau river are plotted against stream length. The statistical estimates from the locally observed flood samples are shown as solid circles while the regional estimates at the gauging stations are marked as open circles. The regional estimates are based on top-kriging without using local flood data. The solid line shows the regionalization for the entire reach. The regional flood moments for Drauhofen are MAF = 511 m³/s, CV = 0.53 and CS = 1.3 which differ significantly from the local moments and those from the temporal expansion of information (Table 3). MAF is lower while CV is larger. Regional CS is much larger than that of the



Figure 8. Time series of observed maximum annual peak discharges of (top) the Drau at Drauhofen and (bottom) the Drau at Amlach.

local flood record, but similar to the CS from the analysis of historical floods.

[26] Similar to the second example, an analysis of the causal factors leading to floods is used to give confidence in the statistical analysis and/or the temporal and spatial information expansion. The Drauhofen gauging station is located immediately downstream of the confluence of the Drau and the Möll rivers. Immediately upstream of the confluence are the Sachsenburg (2561 km²) and Möllbrücke (1096 km²) stream gauges, so the Drauhofen runoff is the sum of the runoff at the two upstream gauges. Long-term continuous runoff observations at Sachsenburg and Möllbrücke have not been available but maximum annual flood peaks exist from 1953. An analysis of the coincidence of the floods suggests that, out of the 55 years of record, in 42 vears the same event produced the maximum annual flood peak at the two gauges. For these 42 years, the specific flood peaks are shown in Figure 10. The coefficient of correlation r is about 0.6. The moments of the sum z of two correlated random variables x and y are [see, e.g., *Plate*, 1993]

$$\mu_z = \mu_x + \mu_y$$

$$\sigma_z^2 = \sigma_x^2 + \sigma_y^2 + 2 \cdot r \cdot \sigma_x \cdot \sigma_y,$$
(3)

where μ and σ are the respective means and standard deviations. If one assumes that the 42 years of coincidence

are representative of the population, and x and y are the Sachsenburg and Möllbrücke flood peaks, the moments at Drauhofen are MAF = 615 m³/s and CV = 0.39. This suggests, that the MAF of the local statistics and the temporal expansion is more realistic than the regional estimate of MAF, while the CVs of the temporal and spatial expansion are more plausible than the CV of the local statistics. The use of local MAF and regional higher moments is consistent with the reasoning of the Index Flood approach [*Dalrymple*, 1960] and the recommendations of

 Table 3. Combination of Data Evidence for the Drauhofen

 Catchment^a

Type of Information	Data and Method	MAF (m ³ /s)	CV	CS	HQ100 (m ³ /s)
Statistics	method of moments, GEV distribution	620	0.21	0.33	957
Temporal	longer flood record of	~ 620	0.32	2.36	1326
×	neighboring station; historical flood information	~620	0.35	1.3	1319
Spatial	top-kriging without local data	511	0.53	1.3	1384
Causal	confluence of Drau and Möll river	615	0.39		
Combination		620	0.39	1.3	1399

^aCatchment is 3674 km².



Figure 9. Longitudinal profiles of the 100-year flood discharges of the Drau river. Statistical estimates at the gauging stations based on locally observed flood data are shown as open circles. Regional estimates are shown as solid circles and solid line.

the UK Flood Estimation Handbook [Institute of Hydrology, 1999, Book 1, Table 5.1] of using regional growth curves. Clearly, MAF can be more reliably estimated from short local records than CV and CS. In line with this reasoning, the plausible moments of example 3 are MAF = $620 \text{ m}^3/\text{s}$, CV = 0.39 and CS = 1.3, which translate into a 100-year flood of 1399 m³/s.

3.4. Example 4: Zöbernbach at Kirchschlag

[27] As a last example, the Zöbernbach at Kirchschlag (113 km²) in southeast Austria is presented. For a statistical analysis 26 years of flood data from 1976 to 2001 are available (Figure 11a). The statistical moments of the flood sample are MAF = $19 \text{ m}^3/\text{s}$, CV = 0.87 and CS = 1.31 which give $HQ_{100} = 72 \text{ m}^3/\text{s}$. Information can be expanded into the past by comparing the flood samples to the longer record of the neighboring stations in the region, for example, Rabnitz at Piringsdorf (117 km²) (Figure 11b), for which observations are available from 1951 to 2001. The moments of the flood sample at Piringsdorf are MAF = $11.6 \text{ m}^3/\text{s}$, CV = 1.25 and CS = 1.81. Owing to the small geographical distance (about 8 km) and the similarities in climate and landforms, the longer flood record of Piringsdorf can be assumed to be representative of the floods that may have occurred in Kirchschlag before observations started. This means that the temporal expansion would in this case point to an increase in CV and CS (Table 4). For the next closest stream gauge, Stoob at Oberpullendorf (149 km², 36 years of record), the increase in CV and CS is smaller with CV and CS of 1.05 and 1.4, respectively. The range of the estimates from the two stream gauges is noted in Table 4 and indicated as a light gray band in Figure 13a.

[28] Information on historical flood events at the Zöbernbach were not available in this study, but *Gutknecht and Watzinger* [2000] analyzed historical archives at Walpersbach, which is located about 20 km north of the catchment outlet. In the period from 1866 to 1996, 10 destructive floods due to convective storms have been reported in Walpersbach. Because of the small geographical distance similarly large floods are likely to occur at Kirchschlag. While the archival information is too vague to obtain

quantitative estimates they are an indicator that the floods at Zöbernbach are possibly larger than what the local flood record indicates. This proxy information is indicated by plusses in Table 4.

[29] A first look at the statistical moments of the observed flood samples of neighboring catchments exhibits a wide scatter. As an example, the CS estimated from the local flood samples are shown in Figure 12. In some catchments, CS is larger than 2, while in nearby catchments CS is sometimes smaller than 0.5. For one catchment north of the Zöbernbach, CS is even negative. There is a similarly large variability in CV (not shown here). Regional estimates of the statistical moments of Kirchschlag based on top-kriging without using local flood data are MAF = $16 \text{ m}^3/\text{s}$, CV = 0.8and CS = 1.1. A closer look at the catchments with small CV and CS values indicates that the flood characteristics in these catchments are controlled by flood control reservoirs [Merz et al., 2008] and hence are not representative of the regional trend. Unaffected flood samples in the region exhibit larger values of CV (between 0.85 and 1.5) and CS is larger than one. The remaining variability can be



Figure 10. Comparison of specific maximum annual peak discharges at Sachsenburg (Drau) and Möllbrücke (Möll) for years with identical events.



Figure 11. Time series of observed maximum annual peak discharges of (top) Zöbernbach at Kirchschlag and (bottom) Rabnitz at Piringsdorf.

explained by the relatively short record lengths. To assess natural flood behavior at Kirchschlag, the catchments subject to flood control were excluded from the regionalization which resulted in MAF = $16 \text{ m}^3/\text{s}$, CV = 0.99 and CS = 1.6using the top-kriging approach without local flood data. However, more than 50% of the stream gauges exhibit some flood control effect, so these regional estimates are associated with large uncertainties. Little weight hence needs to be given to these estimates when combining the various sources of information. A multiple regression with longterm mean annual precipitation, the 95% quantiles of hourly rainfall and mean runoff coefficients as explanatory variables, and including all stations in the regression analysis, gives MAF = 23 m³/s, CV = 0.86 and CS = 1.48 while excluding all affected stations increases CV to 0.92 and CS to 1.56. The range of regional estimates depending on whether stream gauges affected by flood control are included or not is indicated in dark gray in Figure 13a and noted in Table 4.

[30] In this example, the regional estimates are inconsistent with the trend given by the temporal expansion. Following the proposed approach of Figure 1, these incon-

sistencies are analyzed. Event runoff coefficients have been plotted in Figure 13b against the return period of the flood peaks which indicate, similarly to example 2, that the runoff coefficients may be much larger for large return periods, so CV and CS are likely larger than those from the statistics. Further insight into the causal factors of floods is provided by the process type classification of Merz and Blöschl [2003] which indicates that the largest floods are mainly short-rain floods and flash floods while the smaller floods are long-rain floods (Figure 13c). This points to a change in mechanism suggesting that convective storms become increasingly important for extreme floods in this catchment. Merz and Blöschl [2003] noted that the flood frequency curves caused by convective rainfall bursts tend to steepen with increasing return period which points to an increase of CV and CS as compared to the local record. An analysis of the landforms in the Kirchschlag catchment corroborates the occurrence of extreme floods (Figure 14). The breaks in the topographic contour lines indicate deeply incised channels which are, apparently, a result of erosive forces during large flood events. The degree of incision of the channels is similar to the Rotach catchment [Merz and Blöschl, 2008,

Type of Information	Data and Method	MAF (m ³ /s)	CV	CS	HQ100 (m ³ /s)
Statistics	methods of moments, GEV distribution.	19	0.87	1.3	72
Temporal	longer records in neighboring catchment; historical flood information	19	1.05 - 1.25 +	1.4–1.8 +	84-100
Spatial	top-kriging without local data, multiple regression	16	0.8 - 0.99	1.1-1.6	56-69
Causal	runoff coefficients; process types; geomorphology/landforms		+ + +	+ + +	
Combination		19	1.2	1.8	97

Table 4. Combination of Data Evidence for the Kirchschlag Catchment^a

^aCatchment is 113 km². Plusses indicate that a piece of information suggests larger moments than the local flood data.



Figure 12. Map of coefficient of skewness (CS) estimated from locally observed flood data for Kirchschlag and neighboring gauges.

Figure 11], but processes are different. The Rotach catchment (90 km²) is located at the northern rim of the high Alps in one of the wettest regions of western Austria with long-term mean annual precipitation of 1794 mm as compared to 835 mm at Kirchschlag. Mean annual floods at Rotach are relatively large, but the flood frequency curve does not increase much for higher return periods. The mean annual flood of Kirchschlag is only one fifth of that in Rotach, although catchment area is larger. One would hence expect that erosion at Kirchschlag is not a result of regular small flood events but rather a result of a few larger events which may not have been sampled by the local flood record. CV and CS may hence be larger than indicated by the local flood record as indicated by plusses in Table 4. In this example, some of the sources of information are rather uncertain. However, the overall trend of the various sources is similar in that it suggests that CV and CS are large which gives most credence to the temporal expansion from neighboring catchments (Table 4). In choosing plausible CV and CS the longer records in neighboring catchments are deemed to provide the most reliable information. Within the range consistent with the data in neighboring catchments (1.05-1.25, 1.4-1.8) the upper limit is considered to be more plausible as the causal information points to large CV and CS. Given that the longer records in neighboring catchments are deemed to be the most reliable pieces of information and are in agreement with local statistics, a

MAF of $19\text{m}^3/\text{s}$ is considered a plausible estimate. The plausible moments at Kirchschlag hence are MAF = $19 \text{ m}^3/\text{s}$, CV = 1.2 and CS = 1.8 which translate into a 100-year flood of 97 m³/s.

4. Summary and Conclusions

[31] In a companion paper [*Merz and Blöschl*, 2008] we argue that it is very useful to expand the information beyond the flood sample at the site of interest to better represent the diversity of flood processes in estimating flood frequencies. In this paper we present a framework of how to combine different sources of information by hydrological reasoning to obtain more informed estimates of flood frequencies. These sources of information include the local flood peak sample and temporal, spatial and causal expansion of information.

[32] To illustrate the proposed framework, four examples from Austria are given. In all four examples the statistical analyses of the flood records do not fully represent the site specific flood behavior in the light of the more complete information. In example 1 the local flood sample overestimates flood discharges as compared to the more comprehensive information while in the other examples the local flood sample underestimates flood discharges. Provided the local estimation procedure is unbiased one would assume that overestimation and underestimation occurs in



Figure 13. (a) Flood frequency plot, (b) runoff coefficients of the associated flood events plotted against the return periods of the flood peaks, and (c) flood frequency plots with the process types indicated. All plots are for Zöbernbach at Kirchschlag.

a similar number of cases. In example 1, an outlier strongly affects the statistical analysis. It is difficult to assess the return period of the outlier from the flood record alone but the extended information helps make a more informed assessment. In example 2 and 3, the flood

records fall into decades with below average flood occurrence. The samples are hence not ergodic and the local statistical analysis appears to underestimate the flood discharges. The examples illustrate that the flood record may not be representative of the population, even if the flood data are



Figure 14. Topographic map of representative landforms of the Zöbernbach catchment. Contour lines are traced as thick black lines to illustrate the degree of incision of the streams.

of good quality and the record length is reasonably long according to flood estimation guidelines [*Deutscher Verband für Wasserwirtschaft und Kulturtechnik*, 1999; *Institute of Hydrology*, 1999]. In the four examples the lengths of the flood records vary between 26 years (example 4) and 53 years (example 1). While more sophisticated estimation procedures may slightly reduce the biases they will not overcome the more fundamental problem of limited information unless additional information beyond the flood peak sample is used.

[33] Temporal information expansion by historical flood analysis and comparisons with longer records of neighboring catchments provided helpful information in most examples. In example 1, the probability of the outlier was estimated with more confidence than on the basis of the flood record alone. In example 3, the statistical moments of the flood records were adjusted for climate variability by analyzing a longer record of a downstream neighbor. However, information expansion into the past is not always possible. In example 2, neither historical flood data nor longer records in the region were available. In example 4, historical information is highly uncertain and only a qualitative estimate can be given. Comparisons to longer records outside the region may introduce additional uncertainty so may not always be appropriate. The strength of the proposed framework is its flexibility in that more weight can be given to other sources of information if one particular source is more uncertain than others. The merits of regional information expansion in improving at-site statistical flood estimates are well documented in the literature [e.g., Institute of Hydrology, 1999]. This is also borne out in examples 1 and 3. However, examples 2 and 4 suggest that care must be taken as the regionalization may not always improve the local estimates. Causal information expansion is often used in the hydrological literature in terms of the derived flood frequency approach or runoff models as alternatives to flood frequency statistics [e.g., Institute of Hydrology, 1999; Pilgrim and Doran, 1993]. The examples of this paper suggest that a formal derived flood frequency model is not necessarily needed to account for process information. Proxy data or indicators can in fact be very well incorporated into the proposed framework of reasoning and combined with temporal or spatial information expansion. For example, in example 2, proxy data are used to corroborate the regionalization approach. The proxy information alone would probably not suffice to come up with flood estimates but combining it with other, more quantitative information, may enhance the confidence with which flood estimates are made.

[34] The framework used here has an element of subjectivity. We argue that this is in fact a strength as it allows to account for local particularities of catchments that cannot be easily incorporated into a formal scheme. These include a rich diversity of hydrological conditions and data availabilities. The main sources of information could, however, be formalized, for example by Bayesian statistics and fuzzy methods. This could be the subject of future work. The process of putting more weight on the sources with the least uncertainty, as proposed in the framework, would then be more quantitative. Also, it should be noted that the traditional choice of quantitative methods is perhaps no less subjective as, often, the flood estimates significantly depend

on the methods chosen. The examples cover a wide range of flood processes, but the variety of processes one encounters in various regions is certainly greater. The purpose of the examples was to illustrate the basic principle of combining complementary sources of information by hydrological reasoning, and analogous procedures apply to other processes. In a similar vein, the estimation methods in this papers have been chosen for illustrative purposes and alternative methods could be used equally well. For example, instead of the top-kriging regionalization approach, multiple-regression or the Region of influence approach could be used. Instead of the Gradex method, more complex derived flood frequency models can be used. The selection of methods used here has been motivated by the available data and our own experience in using them. Similarly, the flood frequency hydrology framework is not limited to using traditional flood moments, and other methods such as L-moments and alternative distribution functions can be used.

[35] The classification of the sources of information into temporal, spatial and causal information is of course not a strict one. Most of the examples have aspects of more than one type. For example, the comparison of longer time series from neighboring catchments to detect periods of below average and above average flooding is presented as temporal information expansion as the focus is on the temporal evolution of flood discharges. However, this has also an element of spatial expansion as information is transposed across catchment boundaries. The classification is used to strengthen the focus on the additional information and the data, concepts and assumptions involved. It should also be noted that the combination of flood information based on reasoning is a rather lengthy process, certainly less straightforward than the simple application of an estimator. We believe that this more involved reasoning is needed for more informed decisions on design floods. The proposed framework was applied in a large study in Austria where 30-, 100and 200-year return period flood discharges were estimated for more than 1000 stream gauge sites [Merz et al., 2008]. This suggests that the framework is certainly applicable in practical cases. The additional benefit of the reasoning is that authorities tend to relate very well to it as it provides some conceptual understanding of how the estimates were obtained. The flood estimates of Merz et al. [2008] were in fact very well accepted by the hydrographic authorities in Austria.

[36] The paper illustrates the benefit of flood frequency estimates based on combining various sources of information for gauged catchments. In ungauged catchments the framework can be applied in a similar way but some of the sources of information will be different. No local runoff data can be used but most of the other sources may be available. In particular, historical archives may provide useful indicators of large flood events. Analyses of the causal factors leading to flooding will also be possible in the absence of a local flood record, for example, through discussions of recent floods with locals and by post flood surveys [*Borga et al.*, 2006]. We believe that the concept of flood frequency hydrology is able to trigger new avenues of research. These may involve quantitative methods of combining data evidence, for example, by Bayesian methods, and by a more causal and comprehensive approach to flood frequency estimation in hydrology.

[37] Acknowledgments. We would like to thank the Austrian Academy of Sciences (Austrian Programme for Advanced Research and Technology (APART) fellowship) and the FWF project P18993-N10 for financial support. We would also like to thank the Austrian Hydrographic Services for providing the hydrographic data and Alberto Montanari and two anonymous reviewers for their constructive comments on the manuscript.

References

- Benito, G., and V. R. Thordycraft (2005), Palaeoflood hydrology and its role in applied hydrological sciences, *J. Hydrol.*, *313*, 3–15, doi:10.1016/ j.jhydrol.2005.02.002.
- Blöschl, G., C. Reszler, and J. Komma (2008), A spatially distributed flash flood forecasting model, *Environ. Model. Software*, 23, 464–478, doi:10.1016/j.envsoft.2007.06.010.
- Bobée, B., and P. Rasmussen (1995), Recent advances in flood frequency analysis, *Rev. Geophys.*, 33(S1), 1111–1116, doi:10.1029/95RG00287.
- Borga, M., F. Zanon, and P. Boscolo (2006), Hydrological and hydrometeorological analysis of the 2003 Val Canale flash flood in north-eastern Italy, *Geophys. Res. Abstr.*, 8, 08690.
- Burn, D. H. (1990), Evaluation of regional flood frequency analysis with a region of influence approach, *Water Resour. Res.*, 26(10), 2257–2265.
- Dalrymple, T. (1960), Flood frequency analysis, U.S. Geol. Surv. Water Supply Pap., 1543A, 80 pp.
- Deutscher Verband für Wasserwirtschaft und Kulturtechnik (1999), Statistische Analyse von Hochwasserabflüssen, *DVWK-Merkblätter zur Wasserwirtschaft H 251*, Wirtschafts- und Verl.-Ges. Gas und Wasser, Bonn, Germany.
- Eagleson, P. S. (1972), Dynamics of flood frequency, *Water Resour. Res.*, 8(4), 878–898, doi:10.1029/WR008i004p00878.
- Guillot, P. (1972), Application of the method of Gradex, in *Floods and Droughts, Proceedings of the Second International Symposium in Hydrology*, edited by E. F. Schulz, V. A. Koelzer, and K. Mahmood, pp. 44–49, Water Resour. Publ., Fort Collins, Colo.
- Gutknecht, D., and A. Watzinger (2000), Untersuchung zur Erfassung und quantitativen Abschätzung von abflussrelevanten Faktoren bei der Ermittlung von Katastrophen-Hochwasserereignissen in kleinen Einzugsgebieten, technical report, Inst. for Hydraul. and Water Resour. Eng., Vienna.
- Gutknecht, D., C. Resler, and G. Blöschl (2002), Das Katastrophenhochwasser vom 7. August 2002 am Kamp-Eine erste Einschätzung, *Elek*trotech. Inf., 119(12), 411–413.
- Gutknecht, D., G. Blöschl, C. Reszler, and H. Heindl (2006), Eine "Mehr-Standbeine"-Ansatz zur Ermittlung von Bemessungshochwässern kleiner Auftretenswahrscheinlichkeit, *Osterreich. Wasser Abfallwirtsch.*, 58(3–4), 44–50.
- Hosking, J. R. M., and J. R. Wallis (1997), Regional Frequency Analysis— An Approach Based on L-Moments, Cambridge Univ. Press, Cambridge, U. K.
- Institute of Hydrology (IH) (1999), *Flood Estimation Handbook*, Wallingford, U. K.
- Kirnbauer, R. (1981), Zur Ermittlung von Bemessungshochwässern im Wasserbau, Wiener Mitt., vol. 42, Inst. für Wasserbau und Ingenieurhydrol., Vienna.
- Komma, J., C. Reszler, G. Blöschl, and T. Haiden (2007), Ensemble prediction of floods—Catchment non-linearity and forecast probabilities, *Nat. Haz. Earth Syst. Sci.*, 7, 431–444.
- Merz, R., and G. Blöschl (2003), A process typology of regional floods, Water Resour. Res., 39(12), 1340, doi:10.1029/2002WR001952.

- Merz, R., and G. Blöschl (2005), Flood frequency regionalization—Spatial proximity vs. catchment attributes, J. Hydrol., 302, 283–306, doi:10.1016/ j.jhydrol.2004.07.018.
- Merz, R., and G. Blöschl (2008), Flood frequency hydrology: 1. Temporal, spatial, and causal expansion of information, *Water Resour. Res.*, 44, W08432, doi:10.1029/2007WR006744.
- Merz, R., G. Blöschl, and U. Piock-Ellena (1999), Zur Anwendbarkeit des Gradex-Verfahrens in Österreich, Osterreich. Wasser Abfallwirtsch., 51(11-12), 291-305.
- Merz, R., G. Blöschl, and J. Parajka (2006), Spatio-temporal variability of event runoff coefficients, *J. Hydrol.*, 331, 591–604, doi:10.1016/j.jhydrol. 2006.06.008.
- Merz, R., G. Blöschl, and G. Humer (2008), National flood discharge mapping in Austria, *Nat. Hazards*, 46(1), doi:10.1007/s11069-007-9181-7.
- Moran, P. M. P. (1957), The statistical treatment of flood flows, *Eos Trans. AGU*, *38*, 519–523.
- Mudelsee, M., M. Börngen, G. Tetzlaff, and U. Grünewald (2004), Extreme floods in central Europe over the past 500 years: Role of cyclone pathways "Zugstrasse Vb," J. Geophys. Res., 109, D23101, doi:10.1029/ 2004JD005034.
- Naghettini, M., K. W. Potter, and T. Illangasekare (1996), Estimating the upper tail of flood-peak frequency distributions using hydrometeorological information, *Water Resour: Res.*, 32(6), 1729–1740, doi:10.1029/ 96WR00200.
- Pilgrim, D. H., and D. G. Doran (1993), Practical criteria for the choice of method for estimating extreme design floods, in *Extreme Hydrological Events: Precipitation, Floods and Droughts*, edited by Z. W. Kundzewicz et al., *IAHS Publ.*, 213, 227–235.
- Plate, E. (1993), Statistik und angewandte Wahrscheinlichkeitslehre f
 ür Bauingenieure, Ernst & Sohn, Berlin.
- Rohner, K., I. Berger, H. Steiger, J. Moser, F. Pichler, and N. Sereinig (2004), Hochwasserchronik Kärnten 792–2003, report, Amt der Kärntner Landesregierung, Abteilung 18, Wasserwirtschaft, Klagenfurt, Germany.
- Sivapalan, M., E. F. Wood, and K. Beven (1990), On hydrologic similarity: 3. A dimensionless flood frequency model using a generalized geomorphologic unit hydrograph and partial area runoff generation, *Water Resour*. *Res.*, 26(1), 43–58.
- Sivapalan, M., G. Blöschl, R. Merz, and D. Gutknecht (2005), Linking flood frequency to long-term water balance: Incorporating effects of seasonality, *Water Resour. Res.*, 41, W06012, doi:10.1029/2004WR003439.
- Skøien, J., R. Merz, and G. Blöschl (2006), Top-kriging—Geostatistics on stream networks, *Hydrol. Earth Syst. Sci.*, 10, 277–287.
- Stedinger, J. R., R. M. Vogel, and E. Foufoula-Georgiou (1993), Frequency analysis of extreme events, in *Handbook of Hydrology*, edited by D. R. Maidment, pp. 18.1–18.66, McGraw-Hill, New York.
- Tasker, G. D. (1987), Regional analysis of flood frequencies, in *Regional Flood Frequency Analysis*, edited by V. P. Singh, pp. 1–9, Reidel, Dordrecht, Netherlands.
- U.S. Geological Survey (1982), Guidelines for determining flood flow frequency, *Bull. 17B*, 183 pp., Hydrol. Subcomm., Washington, D. C.
- Wiesbauer, H. (2005), Wasser im Weinviertel, report, Amt der NÖ Landesregierung, Gruppe Wasser, St. Pölten, Austria.
- Wiesbauer, H. (2007), Historische Überflutungen am Kamp, in *Extreme Abflussereignisse*, *Wiener Mitt.*, vil. 206, edited by D. Gutknech, pp. 43–58, Inst. für Wasserbau und Ingenieurhydrol., Vienna.
- Wood, E., and I. Rodriguez-Iturbe (1975), Bayesian inference and decision making for extreme hydrologic events, *Water Resour. Res.*, 11(4), 533– 542.

G. Blöschl and R. Merz, Institute for Hydraulic and Water Resources Engineering, Vienna University of Technology, Karlsplatz 12/223, Vienna A-1040, Austria. (merz@hydro.tuwien.ac.at)